Tracking Solar Eruptions to Their Impact on Earth

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In June 2015, the Sun emitted several M-Class flares over a 2-day period. These flares were concurrent with several coronal mass ejections (CMEs) that occurred over a 5-day period. The result of these flares and CMEs was disturbances to propagation. Let's track the CMEs and flares from the beginning to their impact on the ionosphere.

The first of four CMEs occurred on June 18 at 1724 UTC. It was classified as a full-halo CME. A full-halo CME is one that shows the explosion all around the occulting disc in the coronagraph image. See Figure 1 for this CME (from SOHO – the Solar and Heliospheric Observatory). In addition to the bright explosion towards the bottom right, the full-halo aspect is evident all around the disk – the lighter white areas. A full-halo CME is Earth-directed.

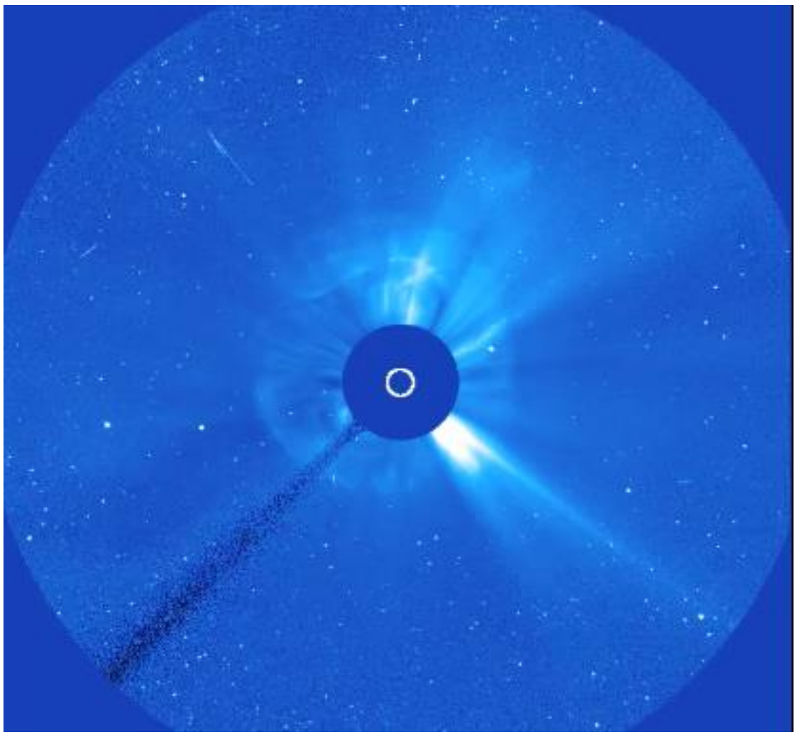

Figure 1 – CME on June 18, 2015 at 1724 UTC

A second CME occurred on June 19 at 0845 UTC. It was a partial-halo CME, which means it was directed slightly away from Earth. A third CME occurred on June 21 at 0142 UTC. It was another full-halo CME.

On June 21 at 0142 UTC, an M2.0 flare erupted concurrent with the third CME referenced above. A second flare of M2.6 magnitude occurred at 0236 UTC, a third flare at M3.8 occurred at 0944 UTC and a fourth flare at M1.1 erupted at 1820 UTC. The next day (June 22) a somewhat long-duration M6.5 flare occurred at 1739 UTC. Figure 2 shows these five M-Class flares. Note that there were several C-Class flares during the June 21-23 period. As a side note, flares are classified by their magnitude in the 1.0 – 8.0 Angstrom range (0.1 – 0.8 nanometers).

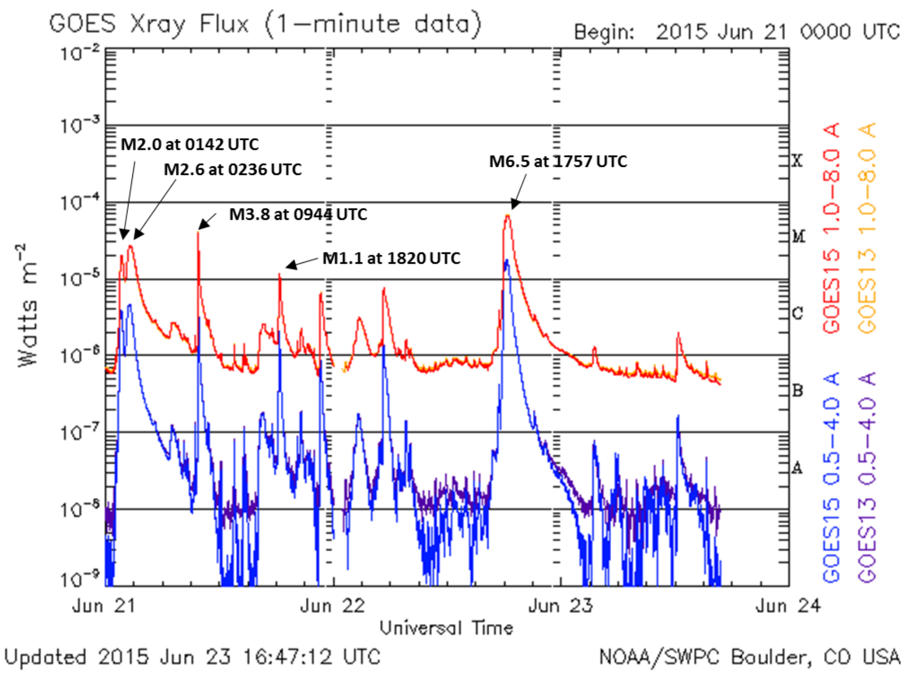

Figure 2 – M-Class flares on June 21 and 22

The instigators (CMEs and flares) of the disturbances to propagation have happened. Now we'll see how the ionosphere responded.

Big flares (M-Class and X-Class) can cause radio blackouts and solar radiation storms. Radio blackouts are due to the electromagnetic radiation at very short wavelengths emitted by flares – wavelengths that can get down to D region altitudes causing increased ionospheric absorption. Since electromagnetic radiation travels at the speed of light, the radio blackout starts on the day side of Earth about 8.5 minutes after the flare eruption. Figure 3 shows the D region absorption due to the big M6.5 flare on June 22.

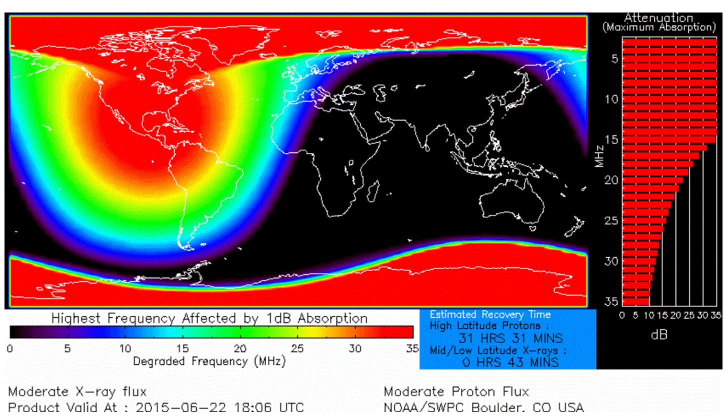

Figure 3 – D region absorption

As stated in the previous paragraph, big flares can also cause solar radiation storms. A solar radiation storm consists of very energetic protons (traveling near the speed of light) funneling into the polar caps and causing excessive D region absorption. Figure 3 also shows the solar radiation storm effects – the red areas in both the northern and southern polar caps. Note that this is a Mercator projection of the Earth, with the polar caps "stretched out" and not circular as they really are. Figure 4 shows detailed measurements of proton flux in the polar cap. Note that the flares early on June 21 started the increase in proton flux.

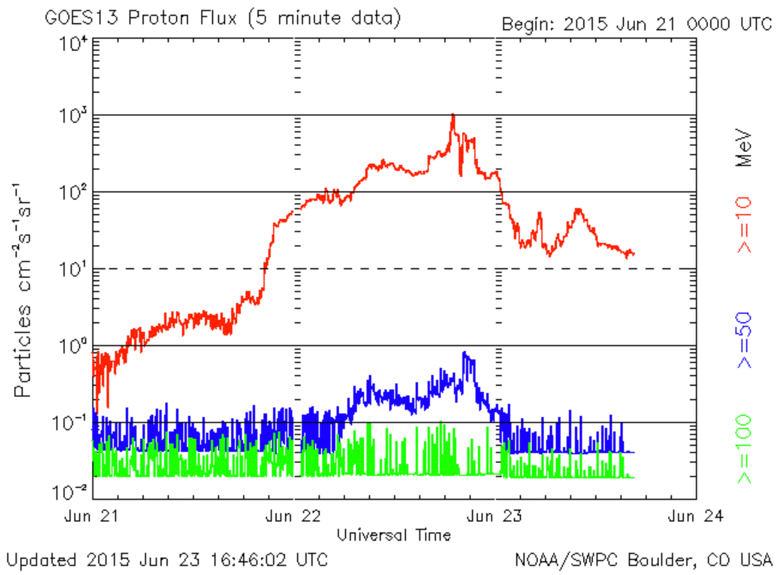

Figure 4 – Proton flux

Now that we've looked at the effects of the solar flares, we can now move to the effects of the CMEs. Figure 5 shows several parameters measured by the ACE (Advanced Composition Explorer) satellite, which is about 1 million miles from Earth on a line from the Earth to the Sun.

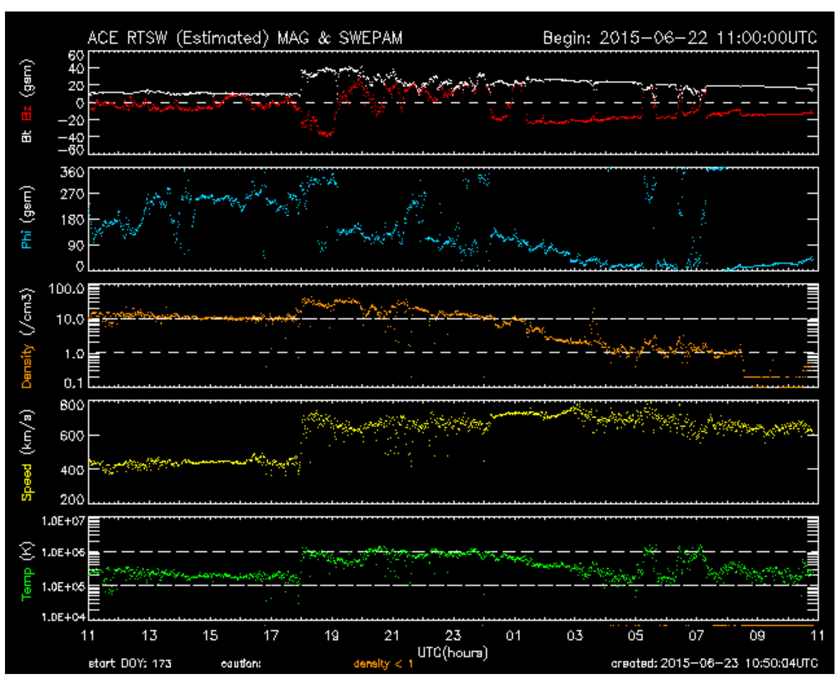

Figure 5 – ACE data

The CMEs started occurring earlier than the flares. The first CME was on June 18, the second was on June 19, and the third was on June 21. The third one propagated faster than the first two, and actually caught up to the first two. The combined effect showed up at ACE (Figure 5) around 1800 UTC on June 22. The two most relevant parameters are the Bz component of the magnetic field (top plot – it went negative) and the solar wind speed (fourth plot from top – it increased).

Remember that the ACE satellite is about 1 million miles from Earth. The effects on Earth will be delayed a bit compared to the effects seen at ACE. Figure 6 shows electron density at geosynchronous altitudes (approximately 22,000 miles).

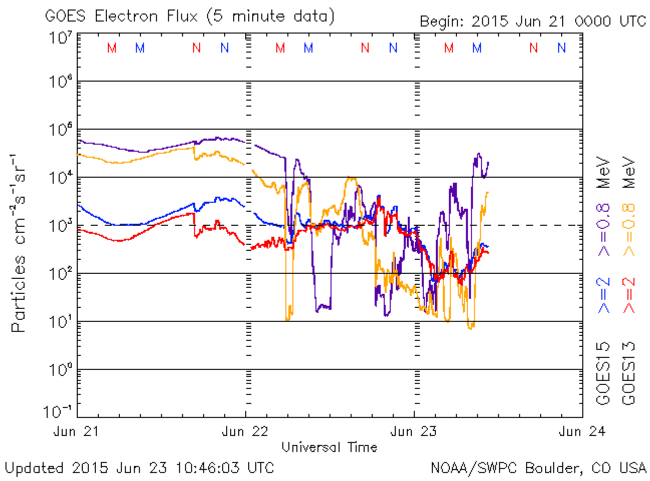

Figure 6 – Electrons at geosynchronous altitudes

When the number of electrons in this plot starts decreasing, that says electrons are being funneled along magnetic fields lines into the auroral zones. This is an important point – electrons that precipitate into the auroral zones to gives us visual aurora do not come directly from the Sun – they are electrons that were trapped in the Earth's magnetosphere and released by the effects of the CME. They then cause the K index to increase as in Figure 7.

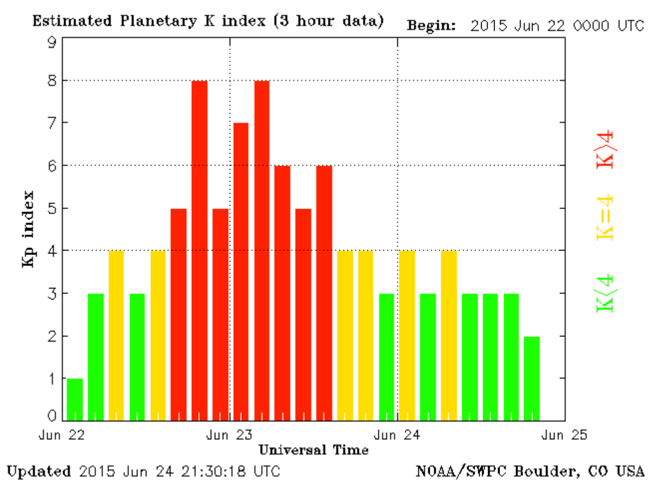

Figure 7 – K indices

The increased K indices in Figure 7 will undoubtedly trigger warnings of aurora as forecasted in Figure 8.

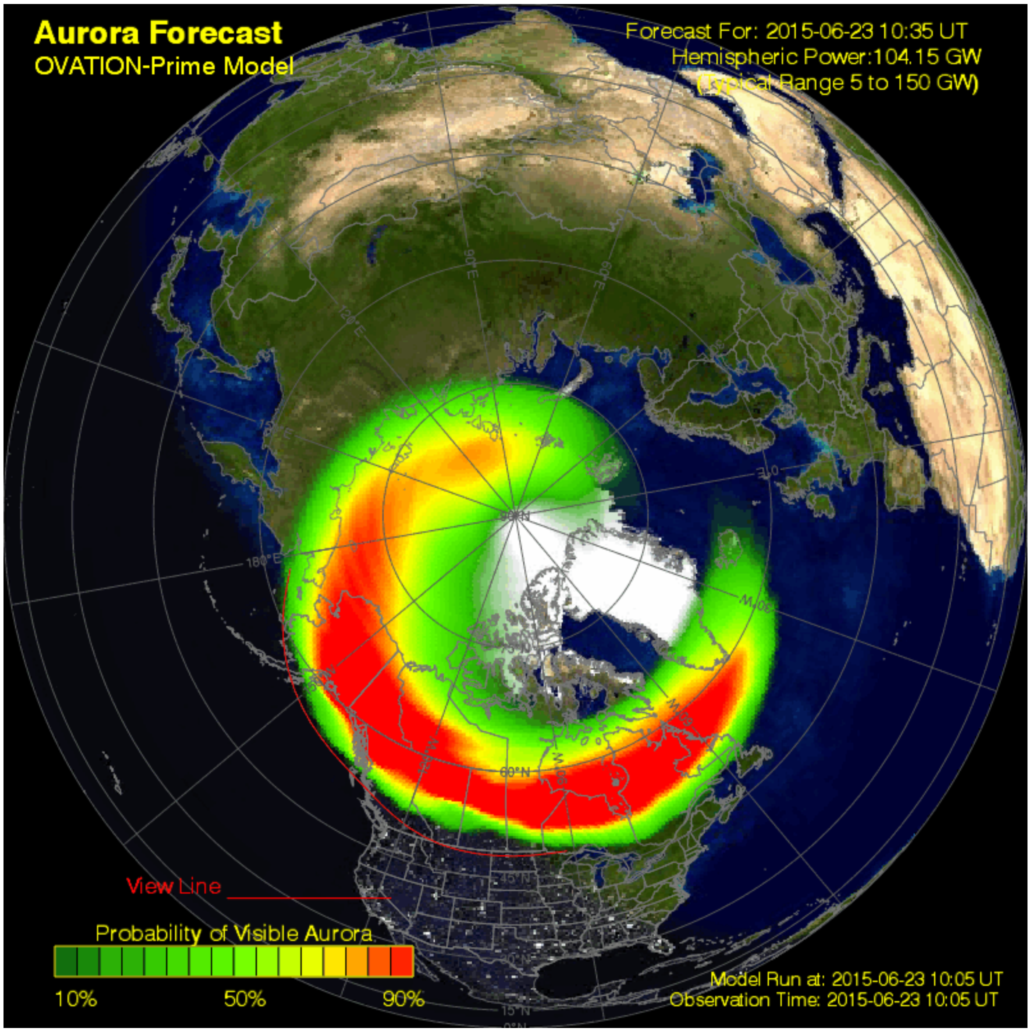

Figure 8 – Aurora forecast

A comment about these auroral forecasts is in order. The orange area is historically where visible aurora has occurred at a similar level of disturbance. It says nothing about aurora that could impact our radio operations, and it does not imply that visual aurora fills the entire area. It's simply where visible aurora has occurred in the past under similar conditions.

Moving forward, we know that elevated K indices can deplete the F2 region of the ionosphere at mid and high latitudes, thus lowering maximum useable frequencies (MUFs). On the plus side, though, the elevated K indices can also enhance the F2 region at low latitudes.

Thus the impact of CMEs (and coronal holes) to the ionosphere is largely negative, and these effects can last several days. In terms of severity, CMEs affecting the ionosphere are generally the top disturbance to propagation due to the duration. It's worth mentioning that CMEs usually occur around solar cycle peak, while coronal holes (which can be just as devastating) usually occur during the declining phase of a solar cycle

A great overall picture of the impact of elevated K indices on the F2 region is given by the STORM Time Empirical Ionospheric Correction Model. It predicts what the F2 region critical frequency (foF2) is doing with respect to the quiet time value. Figure 9 shows the prediction for these June 2015 CMEs.

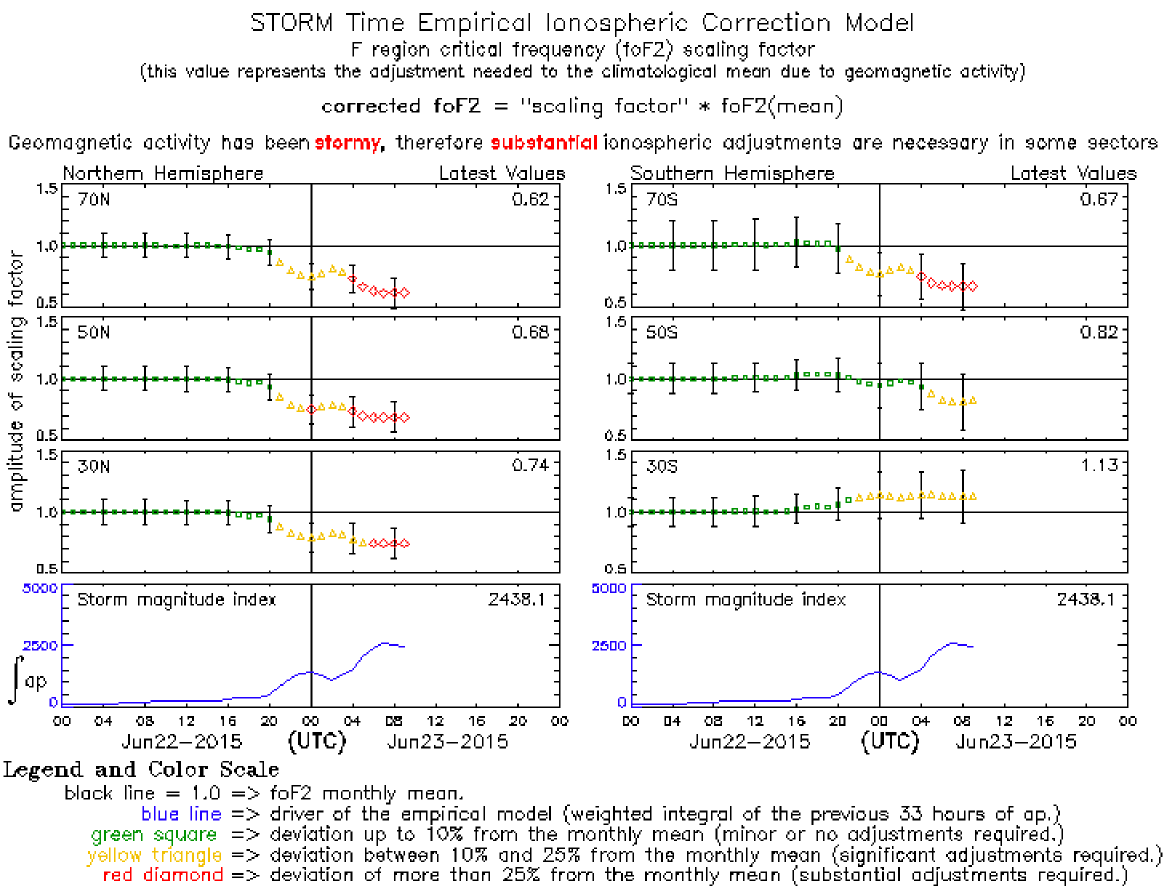

Figure 9 – Impact to the F2 region

Note that the northern hemisphere F2 region at all latitudes and the southern hemisphere at mid and high latitudes are predicted to have significant electron density depletion. But the southern hemisphere at low latitudes is predicted to be enhanced a bit. What this tells you is you'll need to move down in frequency for most paths from your QTH to your target area. But if your path to your target area stays at low southern latitudes, you may want to try a higher frequency.

In summary, we've tracked eruptions on the Sun to their impact as disturbances to propagation. Let's finish by putting together a flow chart to hopefully give a better understanding of these complicated processes. Figure 10 on the next page does this.

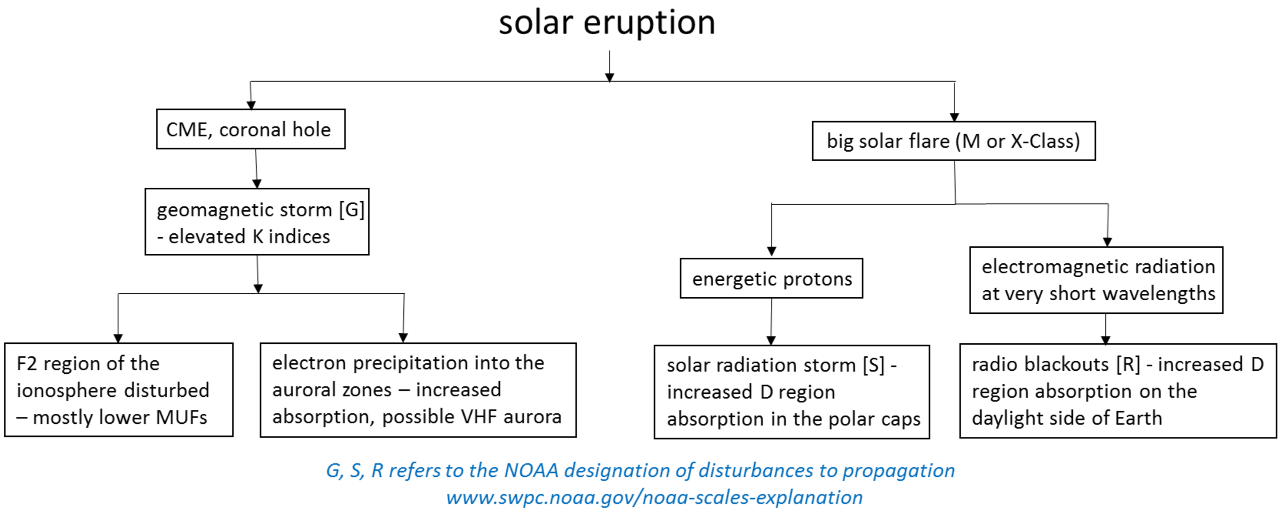

Figure 10 – Flow diagram of disturbances to propagation